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Experimental consequences of one-parameter no-scale supergravity models

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ABSTRACT

We consider the experimental predictions of two *one-parameter* no-scale $SU(5) \times U(1)$ supergravity models with string-inspired moduli and dilaton seeds of supersymmetry breaking. These predictions have been considerably sharpened with the new information on the top-quark mass from the Tevatron, and the actual measurement of the $B(b \rightarrow s\gamma)$ branching ratio from CLEO. In particular, the sign of the Higgs mixing parameter μ is fixed. A more precise measurement of the top-quark mass above (below) ≈ 160 GeV would disfavor the dilaton (moduli) scenario. Similarly a measurement of the lightest Higgs-boson mass above 90 GeV (below 100 GeV) would disfavor the dilaton (moduli) scenario. At the Tevatron with 100 pb^{-1} , the reach into parameter space is significant only in the dilaton scenario ($m_{\chi_1^\pm} \lesssim 80$ GeV) via the trilepton and top-squark signals. At LEP II the dilaton scenario could be probed up to the kinematical limit via chargino and top-squark pair production, and the discovery of the lightest Higgs boson is guaranteed. In the moduli scenario only selectron pair production looks promising. We also calculate the supersymmetric contribution to the anomalous magnetic moment of the muon.

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1 Introduction

Experimental tests of supersymmetric models have become quite topical with the advent of high-energy colliders such as the Tevatron and LEP, and their planned or proposed upgrades. Since the expected scale of supersymmetry is no lower than the electroweak scale, it is not surprising that supersymmetric particles have yet to be found, even though they may be “just around the corner”. In working out the predictions for experimental measurables, one must resort to sensible models of low-energy supersymmetry, which in all generality are described by a large number of parameters. The explicit or implicit choice of a theoretical “framework” to reduce the size of the parameter space is therefore mandatory. The typical framework consists of a supergravity theory with minimal matter content and universal soft-supersymmetry-breaking parameters, and radiative breaking of the electroweak symmetry. Only four parameters are then needed to describe models within this framework: $m_{1/2}, m_0, A, \tan \beta$ [1].

Further reduction in the number of model parameters can be accomplished by invoking the physics of superstrings, as the underlying theory behind the effective supergravity model one chooses. However, the superstring framework is likely not consistent with the Minimal Supersymmetric Standard Model (MSSM) matter content, since unification of the gauge couplings should not occur until the string scale ($M_{\text{string}} \sim 10^{18}$ GeV) is reached. Moreover, traditional GUT models are not easily obtained in string model-building. Therefore we are led to consider a prototype GUST (Grand Unified Superstring Theory) based on the gauge group $SU(5) \times U(1)$ [2] with additional intermediate-scale particles to unify at the string scale [3]. The motivations for $SU(5) \times U(1)$ model building have been elaborated elsewhere [4]. Of particular relevance are the natural suppression of dimension-five proton decay operators, the elegant doublet-triplet splitting mechanism, and the novel see-saw mechanism. Also, usual Yukawa coupling unification is not required in $SU(5) \times U(1)$. Concrete string models based on the gauge group $SU(5) \times U(1)$ has also been obtained and explored in detail [5].

Within the string framework one can study ansätze for the soft-supersymmetry-breaking parameters [6]. We consider such assumptions which are also *universal*, and entail relations of the form: $m_0 = m_0(m_{1/2})$ and $A = A(m_{1/2})$. We thus obtain a two-dimensional parameter space $(m_{1/2}, \tan \beta)$. As a last step in the reduction process, we study two specific scenarios in which the supersymmetry breaking parameter associated with the Higgs mixing term μ is also determined (*i.e.*, $B = B(m_{1/2})$), *i.e.*, ‘strict no-scale $SU(5) \times U(1)$ supergravity’. These assumptions occur naturally in supersymmetry breaking scenarios driven by the F -terms of the moduli or dilaton fields

- moduli scenario [7]:

$$m_0 = 0, \quad A = 0, \quad B = 0. \quad (1)$$

- dilaton scenario [6]:

$$m_0 = \frac{1}{\sqrt{3}}m_{1/2}, \quad A = -m_{1/2}, \quad B = \frac{2}{\sqrt{3}}m_{1/2}. \quad (2)$$

These two scenarios are *one-parameter* models, since we can trade $B = B(m_{1/2})$ for $\tan \beta = \tan \beta(m_{1/2})$. They also have a dependence on the top-quark mass, and the sign of the Higgs mixing parameter μ .

The final parameter $m_{1/2}$, *i.e.*, the scale of the supersymmetric spectrum, can be determined dynamically in the no-scale supergravity framework [8]. In this framework one starts with a supergravity theory with a flat direction which leaves the gravitino mass undetermined at the classical level. This theory also has two very healthy properties regarding the vacuum energy: (i) it vanishes at tree-level [9], and (ii) it has no large one-loop corrections (*i.e.*, $\text{Str } \mathcal{M}^2 = 0$) [7]. In this case the vacuum energy is at most $\mathcal{O}(m_W^4)$. Minimization of the electroweak effective potential with respect to the field corresponding to the flat direction determines in principle the scale of supersymmetry breaking [10]. In this spirit we study the present one-parameter models keeping in mind that the ultimate parameter will be determined eventually by the no-scale mechanism in specific string models.

This paper is organized as follows. In section 2 we explore the constraints on the parameter space of these models and describe their sparticle and Higgs-boson spectrum. In section 3 we update the calculation of $B(b \rightarrow s\gamma)$ and contrast it with the latest CLEO results. In section 4 we study the experimental signals for these models at the Tevatron (squark-gluino, trileptons, top-squarks, top-quark decays), LEP II (Higgs bosons, charginos, selectrons, and top-squarks), and HERA (elastic selectron-neutralino and chargino-sneutrino production). Finally in section 5 we summarize our conclusions.

2 Parameter space and spectrum

The one-dimensional parameter space of the models described above can be represented in the $(m_{\chi_1^\pm}, \tan \beta)$ plane by the relation $\tan \beta = \tan \beta(m_{\chi_1^\pm})$. This exercise has been carried out for the moduli and dilaton scenarios first in Refs. [11] and [12] respectively. The results depend on the value of m_t and the sign of μ . In the moduli scenario one can show [11] that for $m_t \lesssim 130$ GeV the condition in Eq. (1) ($B = 0$) can only be satisfied for $\mu > 0$, whereas for $m_t \gtrsim 135$ GeV this condition requires $\mu < 0$. In the dilaton scenario the corresponding condition in Eq. (2) ($B = (2/\sqrt{3})m_{1/2}$) can only be satisfied for $\mu < 0$ [12]. The reason for these restrictions is that μ and B are determined by the radiative electroweak symmetry breaking constraint, and this depends on m_t .

The above quoted values of m_t are running masses which are related to the experimentally observable pole masses via [13]

$$m_t^{\text{pole}} = m_t(m_t) \left[1 + \frac{4}{3} \frac{\alpha_s(m_t)}{\pi} + K_t \left(\frac{\alpha_s(m_t)}{\pi} \right)^2 \right] \quad (3)$$

where

$$K_t = 16.11 - 1.04 \sum_{m_{q_i} < m_t} \left(1 - \frac{m_{q_i}}{m_t}\right) \approx 11. \quad (4)$$

Thus we obtain $m_t^{\text{pole}} \approx 1.07m_t$. Taking the recently announced CDF measurement at face value, $m_t^{\text{pole}} = 174 \pm 17 \text{ GeV}$ [14], we can see that $m_t = 130 \text{ GeV} \leftrightarrow m_t^{\text{pole}} = 139 \text{ GeV}$ is more than 2σ too low. On the other hand, fits to all electroweak data prefer a lower top-quark mass, when the Higgs-boson mass is restricted to be light (as expected in a supersymmetric theory). The latest global fit gives $m_t^{\text{pole}} = 162 \pm 9 \text{ GeV}$ [15], and $m_t = 130 \text{ GeV}$ is again more than 2σ too low. Thus we conclude that in the moduli scenario one must have $\mu < 0$, since $\mu > 0$ can only occur for values of m_t which are in gross disagreement with present experimental data. Interestingly enough, both one-parameter models are viable only for $\mu < 0$. All sparticle and Higgs boson masses and the calculations based on them have a dependence on m_t . As discussed below, the m_t dependence is small in the dilaton scenario, but it can be significant in the moduli scenario. Unless otherwise stated, in what follows we take $m_t = 150 \text{ GeV} \leftrightarrow m_t^{\text{pole}} = 160 \text{ GeV}$ as a representative value.

The calculated value of $\tan\beta$, as outlined above, is shown in Fig. 1. The various symbols used to denote the points will be discussed below.

- *Dilaton scenario.* The dependence on $m_{\chi_1^\pm}$ is very mild: $\tan\beta \approx 1.4$. The dependence on m_t is also mild; $m_t^{\text{pole}} = 160 \text{ GeV}$ is shown in Fig. 1. However, for $\tan\beta = 1.4$ one must have $m_t \lesssim 155 \text{ GeV} \leftrightarrow m_t^{\text{pole}} \lesssim 165 \text{ GeV}$ in order to avoid a Landau pole in the evolution of λ_t up to the unification scale. This upper limit on m_t^{pole} is well within all presently known limits on m_t .
- *Moduli scenario.* The results are rather m_t dependent ($m_t^{\text{pole}} = 160, 170, 180 \text{ GeV}$ are shown in Fig. 1), with $\tan\beta$ decreasing with increasing values of m_t :

$$\begin{aligned} \tan\beta &\approx 17.7 - 23.1 && \text{for } m_t^{\text{pole}} = 150 \text{ GeV}, \\ \tan\beta &\approx 12.4 - 18.4 && \text{for } m_t^{\text{pole}} = 160 \text{ GeV}, \\ \tan\beta &\approx 8.25 - 13.1 && \text{for } m_t^{\text{pole}} = 170 \text{ GeV}, \\ \tan\beta &\approx 5.53 - 8.53 && \text{for } m_t^{\text{pole}} = 180 \text{ GeV}. \end{aligned}$$

The range of $\tan\beta$ values indicates the monotonic increase with $m_{\chi_1^\pm}$.

For a chosen value of m_t we can then calculate the sparticle and Higgs boson spectrum as a function of $m_{\chi_1^\pm}$. After this is done, the current experimental lower bounds on the sparticle and Higgs-boson masses (most importantly $m_h \gtrsim 64 \text{ GeV}$ and $m_{\chi_1^\pm} \gtrsim 45 \text{ GeV}$) are enforced and the actual allowed parameter space results. The neutralino and chargino masses are shown in Fig. 2, the slepton and Higgs-boson masses, and the value of μ in Fig. 3, and the gluino and squark masses in Fig. 4. One can see that most of the masses are nearly linear functions of $m_{\chi_1^\pm}$, although the slope

depends on the scenario. Common result are the relations:

$$m_{\chi_1^\pm} \approx m_{\chi_2^0} \approx 2m_{\chi_1^0}, \quad (5)$$

$$m_{\chi_3^0} \approx m_{\chi_3^\pm} \approx m_{\chi_2^\pm} \approx |\mu|, \quad (6)$$

$$m_{\tilde{g}} \approx 3.3m_{\chi_1^\pm} + 90 \text{ GeV}. \quad (7)$$

Another common feature is the little variability of m_h with $m_{\chi_1^\pm}$:

$$m_h \approx 100 - 115 \text{ GeV}, \quad \text{moduli scenario}; \quad (8)$$

$$m_h \approx 64 - 88 \text{ GeV}, \quad \text{dilaton scenario}. \quad (9)$$

In fact, the two Higgs-mass ranges do not overlap and thus a measurement of m_h would discriminate between the two models. Note also that the three Higgs bosons beyond the lightest one are very close in mass (especially in the dilaton scenario, see Fig. 3) and not light: $m_{H^\pm} \gtrsim 160$ (400) GeV in the moduli (dilaton) scenario.

In the moduli scenario the stau mass eigenstates are significantly split from the corresponding selectron (and smuon) masses (see Fig. 3). This is not the case for the dilaton scenario where they are largely degenerate. These facts are easily understood in terms of the value of m_0 in the two scenarios. Regarding the gluino and squark masses (see Fig. 4), the “average” squark mass (*i.e.*, $m_{\tilde{q}} = (m_{\tilde{u}_L} + m_{\tilde{u}_R} + m_{\tilde{d}_L} + m_{\tilde{d}_R})/4$, with about $\pm 2\%$ split around the average) is very close to the gluino mass

$$m_{\tilde{q}} \approx 0.97m_{\tilde{g}} \gtrsim 255 \text{ GeV}, \quad \text{moduli scenario}; \quad (10)$$

$$m_{\tilde{q}} \approx 1.01m_{\tilde{g}} \gtrsim 260 \text{ GeV}, \quad \text{dilaton scenario}; \quad (11)$$

and both are higher than the present Tevatron sensitivity. We note in passing that the potentially large difference between the running gluino mass $m_{\tilde{g}}$ and the pole gluino mass $m_{\tilde{g}}^{\text{pole}}$ [16]

$$m_{\tilde{g}}^{\text{pole}} = m_{\tilde{g}} \left[1 + \frac{\alpha_s}{\pi} \left(3 + \frac{1}{4} \sum_{\tilde{q}} \log \frac{m_{\tilde{q}}}{m_{\tilde{g}}} \right) \right] \quad (12)$$

is naturally suppressed in these models because of the near degeneracy of gluino and squark masses. We find $m_{\tilde{g}}^{\text{pole}} \approx 1.1m_{\tilde{g}}$.

The situation is quite different for the third-generation squark masses, which are significantly split from $m_{\tilde{q}}$, except for \tilde{b}_2 : $m_{\tilde{b}_2} \approx m_{\tilde{q}}$. The most striking departure is that of the lightest top-squark \tilde{t}_1 . The implications of a light top-squark in the dilaton scenario have been recently discussed in Ref. [17], and will be re-emphasized below. We should add that in this scenario the small value of $\tan \beta$ (≈ 1.4) and the light top-squarks would appear to imply very small tree-level ($\propto \cos^2 2\beta$) and one-loop ($\propto \ln(m_{\tilde{t}_1} m_{\tilde{t}_2}/m_t^2)$) contributions to m_h^2 . In practice, the one-loop contribution to m_h turns out to be sizeable enough because of the often-neglected top-squark mixing effect which adds a large positive term $\sim (m_{\tilde{t}_1}^2 - m_{\tilde{t}_2}^2) \frac{1}{2} \frac{\sin^2 2\theta_t}{m_t^2} \ln(m_{\tilde{t}_1}^2/m_{\tilde{t}_2}^2)$ to the usual piece [18].

As noted above, in the moduli scenario the allowed values of $\tan\beta$ depend strongly on m_t^{pole} . The calculated value of μ also depends on m_t : $\mu(m_t) \propto m_t$ to good approximation in the range of interest. The lightest Higgs-boson mass also depends on m_t : the upper limit in Eq. (8) increases to 120 (125) for $m_t^{\text{pole}} = 170$ (180) GeV. The squarks and sleptons are only slightly affected via their (small) $\tan\beta$ dependence. Even the lightest top-squark is not affected by more than $\pm 2\%$.

We have also calculated the relic abundance of the lightest neutralino $\Omega_\chi h_0^2$ following the methods of Ref. [19]. The results are shown in Fig. 5. We get $\Omega_\chi h_0^2 \lesssim 0.25$ (0.9) in the moduli (dilaton) scenario. These results are automatically consistent with cosmological expectations (*i.e.*, $\Omega_\chi h_0^2 < 1$). The structure on the curves (especially in the dilaton scenario) corresponds to s -channel h and Z poles in the annihilation cross section. The dotted line in the moduli scenario reflects the m_t dependence ($m^{\text{pole}} = 180$ GeV for this line) via the different $\tan\beta$ and μ values.

3 $b \rightarrow s\gamma$

There are several indirect experimental constraints which can be applied to $SU(5) \times U(1)$ supergravity models. For the case of two-parameter models of this kind these constraints have been discussed in Ref. [20]. It turns out that the only one of relevance for the one-parameter models is that from $B(b \rightarrow s\gamma)$. An analysis of this constraint in a variety of supergravity models has recently been performed in Ref. [21]. Here we update this analysis for the one-parameter models in light of the most recent CLEO experimental result [22]

$$B(b \rightarrow s\gamma) = (1 - 4) \times 10^{-4}, \quad \text{at 95\%C.L.} \quad (13)$$

In Fig. 6 we show the calculated value of $B(b \rightarrow s\gamma)$ in both scenarios (for $m_t^{\text{pole}} = 160$ GeV). The latest CLEO limits are indicated by the solid lines, with the arrows pointing into the allowed region. The Standard Model result is also shown. As explained in Ref. [21], there is significant theoretical uncertainty on the value of $B(b \rightarrow s\gamma)$, mostly from next-to-leading order QCD corrections. We have roughly quantified this uncertainty by using a leading order calculation but allowing the renormalization scale to vary between $m_b/2$ and $2m_b$. This variation gives the dotted lines above and below the solid lines in Fig. 6. The same procedure is used to estimate the Standard Model uncertainty, which shows that the data agree well with the Standard Model. In fact, the theoretical uncertainty in the Standard Model prediction is *larger* than the present 1σ experimental uncertainty [22]. In the moduli scenario there is further uncertainty because the value of m_t affects the calculated value of $\tan\beta$. From Fig. 1 we see that larger values of m_t^{pole} decrease $\tan\beta$, and this leads to larger values of $B(b \rightarrow s\gamma)$: the dash-dot line represents the result ($\mu = m_b$) for $m_t^{\text{pole}} = 180$ GeV.

In the one-parameter models, we consider points in parameter space to be “excluded” if their interval of uncertainty does not overlap with that in Eq. (13); these are denoted by crosses (‘ \times ’) in Fig. 1. In the moduli scenario, this constraint

requires $m_{\chi_1^\pm} \gtrsim 120$ GeV for $m_t^{\text{pole}} = 160$ GeV, but only $m_{\chi_1^\pm} \gtrsim 75$ GeV for $m_t^{\text{pole}} = 170$ GeV, and there is no constraint for $m_t^{\text{pole}} = 180$ GeV. In the dilaton scenario, because the allowed values of $\tan\beta$ are small, the constraint is rather mild, only requiring $m_{\chi_1^\pm} \gtrsim 50$ GeV. Stricter constraints can be obtained by allowing less experimental uncertainty (*e.g.*, 1σ) or less theoretical uncertainty, both of which are unwise things to do. We have also identified “preferred” points whose interval of uncertainty overlaps with the corresponding Standard Model interval; these are denoted by diamonds (\diamond) in Fig. 1. From this vantage point, the dilaton scenario or the moduli scenario with somewhat heavy top-quark look quite promising.

4 Experimental predictions

We now discuss the experimental signatures of these one-parameter models at the Tevatron, LEP II, and HERA. For this analysis we consider only the points still allowed by the $b \rightarrow s\gamma$ constraint, *i.e.*, those denoted by dots and diamonds in Fig. 1.

4.1 Tevatron

We consider the present-day $\sqrt{s} = 1.8$ TeV Tevatron with an estimated integrated luminosity of $\sim 100 \text{ pb}^{-1}$ at the end of the on-going Run IB. Three supersymmetric signals could be observed: trileptons from chargino-neutralino production, large missing energy from squark-gluino production, and soft dileptons from top-squark production. All three signals could be observable in the dilaton scenario; only the squark-gluino signal may be observable in the moduli scenario.

- *Neutralinos and charginos.* These are produced in the reaction $p\bar{p} \rightarrow \chi_1^\pm \chi_2^0 X$ [23], and when required to decay leptonically yield a trilepton signal [24]. The cross section is basically a monotonically decreasing function of $m_{\chi_1^\pm}$, whereas the leptonic (and hadronic) branching fractions (given in Fig. 7) are greatly model dependent and vary as a function of the single parameter. Our calculations have been performed as outlined in Ref. [25]. In the moduli scenario there is an enhancement of the chargino leptonic branching fraction because of the presence of light sleptons (*e.g.*, $\chi_1^\pm \rightarrow \ell^\pm \tilde{\nu}$). However, this gain is undone by the suppressed neutralino leptonic branching fraction also because of the light sleptons (*i.e.*, $\chi_2^0 \rightarrow \nu \tilde{\nu}$). In contrast, in the dilaton scenario both branching fractions are comparable. However, in this case for $m_{\chi_1^\pm} \gtrsim 165$ GeV the spoiler mode $\chi_2^0 \rightarrow \chi_1^0 h$ opens up and the neutralino leptonic branching fraction becomes negligible.

The trilepton rates are given in Fig. 8, where we indicate by a dashed line the present CDF upper limit obtained with $\sim 20 \text{ pb}^{-1}$ of data [26]. By the end of the on-going Run IB the integrated luminosity is estimated at $\sim 100 \text{ pb}^{-1}$ per detector. If no events are observed, one could estimate an increase in sensitivity

Table 1: Cross sections at the Tevatron (in pb) for $p\bar{p} \rightarrow \tilde{t}_1 \tilde{t}_1^* X$ [29] and $p\bar{p} \rightarrow t\bar{t} X$ [30]. All masses in GeV.

$m_{\tilde{t}_1}$	70	80	90	100	112	m_t	120	140	160	180
$\sigma(\tilde{t}_1 \tilde{t}_1^*)$	60	30	15	8	4	$\sigma(t\bar{t})$	39	17	8	4

by a factor of 4 (assuming 80% efficiency in recording data) per experiment. Combining both experiments the sensitivity would be even higher (say ~ 6 times better). In Fig. 8 we show the estimated sensitivity range as the area between the dotted lines. In the dilaton scenario we estimate the reach at $m_{\chi_1^\pm} \lesssim (80 - 90)$ GeV. On the other hand, in the moduli scenario the rates are small, but there may be a small observable window for $m_{\chi_1^\pm} \approx 100$ GeV. However, because of the constraints from $b \rightarrow s\gamma$, such values of $m_{\chi_1^\pm}$ are allowed only for $m_t^{\text{pole}} \gtrsim 165$ GeV.

- *Gluino and squarks.* Since in these models we obtain $m_{\tilde{q}} \approx m_{\tilde{g}}$, the multi-jet missing-energy signal is enhanced. In both scenarios we also obtain a lower bound of ~ 260 GeV which makes this signal almost kinematically inaccessible. Indeed, the reach with 100 pb^{-1} is estimated at $m_{\tilde{q}} \approx m_{\tilde{g}} \lesssim 300 \text{ GeV} \leftrightarrow m_{\chi_1^\pm} \lesssim 60 \text{ GeV}$ [27].
- *Top-squarks.* Direct \tilde{t}_1 pair production at the Tevatron (via the dilepton mode) has been shown recently [28] to be sensitive to $m_{\tilde{t}_1} \lesssim 100$ GeV by the end of Run IB, provided the chargino leptonic branching fraction is taken to be $\sim 20\%$. In the dilaton scenario \tilde{t}_1 can be rather light ($m_{\tilde{t}_1} \gtrsim 70$ GeV) and the chargino branching fractions are $\sim 40\%$ (see Fig. 7). In Ref. [28], with a “bigness” $B = |p_T(\ell^+)| + |p_T(\ell^-)| + |\cancel{E}_T|$ cut of $B < 100$ GeV, the $t\bar{t}$ (with $m_t = 170$ GeV) and W^+W^- backgrounds are estimated at 14 fb and 10 fb respectively. With 100 pb^{-1} , a 5σ signal above this background requires $(\sigma B)_{\text{dileptons}} \gtrsim 75 \text{ fb}$. From Fig. 10 in Ref. [28] it appears then that $m_{\tilde{t}_1} \lesssim 130$ GeV could be probed in this case of enhanced branching fractions. In the moduli scenario the top-squarks are too heavy to be detectable ($m_{\tilde{t}_1} \gtrsim 160$ GeV).
- *Soft dileptons.* In the dilaton scenario, if \tilde{t}_1 is light enough, events may already be present in the existing data sample. The cross section for pair-production of the lightest top-squarks $\sigma(\tilde{t}_1 \tilde{t}_1^*)$ depends solely on $m_{\tilde{t}_1}$ [29] and is given for a sampling of values in Table 1. Since in the dilaton scenario $m_{\tilde{t}_1} > m_{\chi_1^\pm} + m_b$ (see Fig. 4), one gets $B(\tilde{t}_1 \rightarrow b\chi_1^\pm) = 1$ (neglecting the small one-loop $\tilde{t}_1 \rightarrow c\chi_1^0$ mode [31]).¹ The charginos then decay leptonically or hadronically with

¹This unsuppressed two-body decay mode of \tilde{t}_1 implies that scalar stoponium will decay too soon to be observable [32].

branching fractions shown in Fig. 7, *i.e.*, $B(\chi_1^\pm \rightarrow \ell \nu_\ell \chi_1^0) \approx 0.4$ ($\ell = e + \mu$) for $m_{\chi_1^\pm} \lesssim 65 \text{ GeV} \leftrightarrow m_{\tilde{t}_1} \lesssim 100 \text{ GeV}$. The most promising signature for light top-squark detection is through the dilepton mode [28]. The ratio of stop-dileptons to top-dileptons is [17]

$$\frac{N_{2\ell}^{\tilde{t}_1 \tilde{t}_1}}{N_{2\ell}^{t\bar{t}}} \approx 3.2 \frac{\sigma(\tilde{t}_1 \tilde{t}_1)}{\sigma(t\bar{t})}. \quad (14)$$

This ratio indicates that for sufficiently light top-squarks there may be a significant number of dilepton events of non-top-quark origin, if the experimental acceptances are tuned accordingly.

Perhaps the most important distinction between top-dileptons and stop-dileptons is their p_T distribution: the (harder) top-dileptons come from the two-body decay of the W boson, whereas the (softer) stop-dileptons come from the (usually) three-body decay of the chargino with masses (in this case) below m_W . Therefore, the top-dilepton data sample is essentially distinct from the stop-dilepton sample. Such distinction is well quantified by the “bigness” (B) parameter mentioned above.

- *Top-quark branching fractions.* In the case of a light top-squark, the channel $t \rightarrow \tilde{t}_1 \chi_1^0$ may be kinematically accessible. In the dilaton scenario for $m_t^{\text{pole}} = 160 \text{ GeV}$ this is the case for $m_{\tilde{t}_1} \lesssim 115 \text{ GeV}$. The calculated values of $B(t \rightarrow \tilde{t}_1 \chi_1^0)$ and $B(t \rightarrow bW)$ are shown in Fig. 9. One can see that if \tilde{t}_1 is light enough, one would expect up to $(0.9)^2 \approx 20\%$ reduction in the number of observed top events relative to the Standard Model prediction. However, this discrepancy would not be observable until a sizeable top-quark sample is collected. For a 2σ effect one would need to measure the $t\bar{t}$ cross section to 10% accuracy, which requires ~ 100 background-subtracted top events. This event sample will not be available before the Main Injector era.

4.2 LEP II

At present it is uncertain what the LEP II beam energy may ultimately be. It is expected that LEP II will turn on in 1996 at $\sqrt{s} \approx 180 \text{ GeV}$, while the highest possible center-of-mass energy is estimated at $\sqrt{s} = 240 \text{ GeV}$. The precise value of \sqrt{s} has two main effects: it determines the kinematical reach for pair-produced particles (such as charginos and selectrons), and it determines the reach in Higgs-boson masses. The latter is of more relevance since for sufficiently high values of $\sqrt{s} (< 240 \text{ GeV})$, it may be possible to cover *all* of the parameter space of these models. For definiteness, unless otherwise stated, in what follows we will set $\sqrt{s} = 200 \text{ GeV}$. We consider four signals: Higgs bosons, charginos, charged sleptons, and top-squarks. The calculations of the first three signals have been performed as described in Ref. [33].

- *Higgs bosons.* These are produced via $e^+e^- \rightarrow Zh$, with $h \rightarrow b\bar{b}$ and b -tagging to reduce the background. The cross section for this process differs from the corresponding Standard Model cross section in two ways: by the factor $\sin^2(\alpha - \beta)$,

and by the ratio $f = B(h \rightarrow b\bar{b})/B(H \rightarrow b\bar{b})_{\text{SM}}$. In the models under consideration, $\sin^2(\alpha - \beta)$ is very close to 1, according to a decoupling phenomenon induced by the radiative electroweak breaking mechanism [34]. In Fig. 10 we show the $h \rightarrow b\bar{b}$ branching fraction which shows that f is usually close to 1, except when the supersymmetric decay mode $h \rightarrow \chi_1^0 \chi_1^0$ is open. This channel is open for $m_h > 2m_{\chi_1^0} \approx m_{\chi_1^\pm}$, *i.e.*, only for the lightest values of m_h , since m_h grows little with $m_{\chi_1^\pm}$, as Fig. 10 shows.

The effective cross sections $\sigma(e^+e^- \rightarrow Zh) \times f$ are shown in Fig. 11. The deviations of the curves from monotonically decreasing functions of m_h , which coincide with the Standard Model prediction, are due to the $h \rightarrow \chi_1^0 \chi_1^0$ erosion of the preferred $h \rightarrow b\bar{b}$ mode. These deviations could be used to differentiate between the Standard Model Higgs boson and the supersymmetric Higgs bosons considered here.

The LEP II sensitivity for Higgs-boson detection is estimated at 0.2 pb for a 3σ effect in 500 pb^{-1} of data [35]. In the moduli scenario this cross section level is reached for $m_h \approx 106$ (114) GeV for $\sqrt{s} = 200$ (210) GeV. From Eq. (8) we see that LEP II would need to run at $\sqrt{s} \approx 210$ GeV to cover the whole parameter space (for $m_t^{\text{pole}} = 160$ GeV). On the other hand, in the dilaton scenario for $\sqrt{s} = 200$ GeV one obtains $\sigma(e^+e^- \rightarrow Zh) \times f > 0.57 \text{ pb}$, which has a 5σ significance for $\mathcal{L} = 170 \text{ pb}^{-1}$. (For $\sqrt{s} = 180$ GeV we obtain $\sigma(e^+e^- \rightarrow Zh) \times f > 0.22 \text{ pb}$, *i.e.*, also observable with sufficiently large \mathcal{L} .) Therefore, LEP II should be able to cover *all* of the parameter space in the dilaton scenario via the Higgs signal. In Fig. 10 we also show a detail of the relation between m_h and $m_{\chi_1^\pm}$ which shows that a lower bound on m_h would immediately translate into a lower bound on the chargino mass, and in turn into a lower bound on all sparticle masses.

- *Charginos.* The preferred signal is the “mixed” decay $(1\ell + 2j)$ in pair-produced charginos. The chargino branching fractions in Fig. 7 indicate that this mode is healthy in the dilaton scenario, but rather suppressed in the moduli scenario. This is revealed in Fig. 12 where we show the “mixed” cross sections in both scenarios. With an estimated 5σ sensitivity of 0.12 pb (for 500 pb^{-1}) [20], one should be able to reach up to $m_{\chi_1^\pm} \lesssim 96$ GeV in the dilaton scenario. The reach should decrease by ~ 10 GeV for $\sqrt{s} = 180$ GeV. In the moduli scenario we obtain $(\sigma B)_{\text{mixed}} < 0.03$, *i.e.*, an unobservable signal. However, the much larger dilepton mode may lead to an observable signal in this case if the W^+W^- background could somehow be dealt with.
- *Sleptons.* At LEP II only in the moduli scenario are the sleptons kinematically accessible (see Fig. 3). The processes of interest are $e^+e^- \rightarrow \tilde{e}_R \tilde{e}_R + \tilde{e}_R \tilde{e}_L$ and $e^+e^- \rightarrow \tilde{\mu}_R \tilde{\mu}_R$, with the further decays $\tilde{e}_{R,L} \rightarrow e \chi_1^0$ and $\tilde{\mu}_R \rightarrow \mu \chi_1^0$ with near 100% branching fractions [33]. The selectron cross section, shown in Fig. 13, is large: $\sigma(e^+e^- \rightarrow \tilde{e}\tilde{e}) > 1 \text{ pb}$ for $m_{\tilde{e}_R} < 80$ GeV. (Note the kink on the

curve when the $\tilde{e}_R\tilde{e}_L$ channel closes.) The 5σ sensitivity for $\mathcal{L} = 100$ (500) pb^{-1} is estimated at 0.47 (0.21) pb [20]. This sensitivity level is reached for $m_{\tilde{e}_R} \approx 84$ (90) GeV and corresponds to $m_{\chi_1^\pm} \approx 92$ (103) GeV (see Fig. 3). Thus, the *indirect* reach for chargino masses is larger than the direct one (via the “mixed” mode). The smuon cross section is much smaller (see Fig. 13) and so are the corresponding reaches in smuon ($m_{\tilde{\mu}_R} \approx 70$ (82) GeV) and chargino masses. Again, these reaches should decrease by ~ 10 GeV for $\sqrt{s} = 180$ GeV.

- *Top-squarks.* These are kinematically accessible only in the dilaton scenario. Moreover, since $m_{\tilde{t}_1} \lesssim 100$ GeV for $m_{\chi_1^\pm} \lesssim 65$ GeV, the reach into the parameter space is not very significant, but a new lower bound on $m_{\tilde{t}_1}$ could be obtained. We consider the process

$$e^+e^- \rightarrow \tilde{t}_1\tilde{t}_1 \rightarrow (b\chi_1^+)(\bar{b}\chi_1^-) \quad (15)$$

with $B(\tilde{t}_1 \rightarrow b\chi_1^\pm) = 1$. The cross section $\sigma(e^+e^- \rightarrow \tilde{t}_1\tilde{t}_1)$ proceeds through s -channel photon and Z exchanges. In the case of Z -exchange, the coupling $Z\tilde{t}_1\tilde{t}_1$ is proportional to $\cos^2\theta_t - \frac{4}{3}\sin^2\theta_W$ and vanishes for $\cos^2\theta_t \approx 0.31$. In the dilaton scenario, for $m_{\tilde{t}_1} \lesssim 100$ GeV we find $\cos^2\theta_t \approx 0.60$ and this cancellation does not occur. The cross section is shown in Fig. 14, and has been calculated including initial state radiation and QCD corrections, as described in Ref. [36]. Depending on the chargino decays, one can have three signatures: $2b + 2\ell$, $2b + 1\ell + 2j$, $2b + 4j$, all with the same branching fraction of $\approx (0.4)^2$ (see Fig. 7). The traditional W^+W^- background is not relevant (unless one ℓ is lost and there is no b -tagging), and probably the channel with the least number of jets (*i.e.*, $2b + 2\ell$) is preferable. Assuming a suitably cut background, three signal events (of any of the three signatures) would be observed for $\sigma(e^+e^- \rightarrow \tilde{t}_1\tilde{t}_1) \gtrsim 0.19$ (0.04) pb with $\mathcal{L} = 100$ (500) pb^{-1} . From Fig. 14 this sensitivity requirement implies a reach of $m_{\tilde{t}_1} \approx 85$ (95) GeV.

4.3 HERA

The weakly interacting particles may be detectable at HERA if they are light enough and if HERA accumulates and integrated luminosity $\mathcal{O}(100 \text{ pb}^{-1})$. So far HERA has accumulated a few pb^{-1} of data and it is expected that eventually it will be producing $25 - 30 \text{ pb}^{-1}$ per year. The supersymmetric signals in $SU(5) \times U(1)$ supergravity have been studied in Ref. [37], where it was shown that the elastic scattering signal, *i.e.*, when the proton remains intact, is the most promising one. The deep-inelastic signal has smaller rates and is plagued with large backgrounds. The reactions of interest are $e^-p \rightarrow \tilde{e}_{L,R}^-\chi_{1,2}^0p$ and $e^-p \rightarrow \tilde{\nu}_e\chi_1^-p$. The total elastic supersymmetric signal is shown in Fig. 15 versus the chargino mass. The dashed line represents the limit of sensitivity with $\mathcal{L} = 200 \text{ pb}^{-1}$ which will yield five “supersymmetric” events. The signal is very small in the dilaton scenario, but may be observable in the moduli scenario. However, considering the timetable for the LEP II and HERA programs, it is quite likely that

LEP II would explore all of the HERA accessible parameter space before HERA does. This outlook may change if new developments in the HERA program would give priority to the search for the right-handed selectron (\tilde{e}_R) which could be rather light in the moduli scenario. At HERA one could also produce top-squark pairs, if they are light enough, as possible in the dilaton scenario. However, the cross section in this case is smaller than 0.01 pb for $m_{\tilde{t}_1} > 70$ GeV and decreases very quickly with increasing values of $m_{\tilde{t}_1}$ [38].

5 Conclusions

We have explored the experimental consequences of well motivated one-parameter no-scale $SU(5) \times U(1)$ supergravity in the moduli and dilaton scenarios. Such models are highly predictive and therefore falsifiable through the many correlations among the experimental observables. In fact, the recent information on the top-quark mass has in effect ruled out half of the parameter space in the moduli scenario, selecting the sign of μ to be negative. Interestingly, this is also the required sign in the dilaton scenario. The top-quark mass dependence is particularly important in these models in other ways as well. In the moduli scenario the calculated values of $\tan \beta$ depend strongly on m_t (see Fig. 1), and thus so do the calculated values of $B(b \rightarrow s\gamma)$, which become quite restrictive for $m_t^{\text{pole}} \lesssim 160$ GeV. On the other hand, in the dilaton scenario values of $m_t^{\text{pole}} \gtrsim 165$ GeV are not allowed. Therefore, future more precise determinations of the top-quark mass are likely to disfavor one the scenarios and support the other. A similar (and partially related) dichotomy is present in the Higgs-boson masses, which are below 90 GeV in the dilaton scenario and above 100 GeV in the moduli scenario.

We concentrated on the experimental signals at present-day facilities: the Tevatron with the expected integrated luminosity at the end of the ongoing run, the forthcoming LEP II upgrade, and HERA. At the Tevatron the traditional squark-gluino signal is enhanced (since $m_{\tilde{q}} \approx m_{\tilde{g}}$) but the possible reach into parameter space is small since $m_{\tilde{q}} \approx m_{\tilde{g}} \gtrsim 260$ GeV is required. The trilepton signal is more promising, although only in the dilaton scenario, where a reach of $m_{\chi_1^\pm} \approx (80 - 90)$ GeV is expected. In this same scenario light top-squarks could be detected for $m_{\tilde{t}_1} \lesssim 130$ GeV $\leftrightarrow m_{\chi_1^\pm} \lesssim 80$ GeV. So through different channels the reach into the parameter space should be similar. In the moduli scenario the reach into parameter space is not promising.

At LEP II the Higgs boson should be readily detectable in the dilaton scenario (for $\sqrt{s} > 180$ GeV), in effect covering the whole parameter space of the model. In fact, even an improved lower bound on m_h will constrain the parameter space immediately by requiring a lower bound on the chargino mass. In the moduli scenario Higgs detection requires $\sqrt{s} \gtrsim 200 - 210$ GeV. In both scenarios, for sufficiently low values of m_h , the supersymmetric channel $h \rightarrow \chi_1^0 \chi_1^0$ is open and decreases the usual $b\bar{b}$ yield in a way which could be used to differentiate between the Standard Model Higgs boson and the supersymmetric Higgs bosons considered here. Charginos should be

readily detectable (via the “mixed” mode) almost up to the kinematical limit ($\sqrt{s}/2$) in the dilaton scenario, but will be hard to detect in the moduli scenario. On the other hand, selectrons should be detectable up to near the kinematical limit in the moduli scenario (corresponding to charginos slightly over the direct kinematical limit), and be kinematically inaccessible in the dilaton scenario. Top-squarks in the dilaton scenario should also be detectable up to near the kinematical limit, although this corresponds to much lighter chargino masses than in the other detection modes.

We conclude that at the Tevatron and LEP II the dilaton scenario is significantly more accessible than the moduli scenario is:

	Tevatron			LEP II			
	$\tilde{q} - \tilde{g}$	χ_1^\pm	\tilde{t}_1	h	χ_1^\pm	\tilde{e}	\tilde{t}_1
moduli	✓	×	×	✓	×	✓	×
dilaton	✓	✓	✓	✓	✓	×	✓

Moreover, in the dilaton scenario LEP II is basically assured the discovery of the Higgs boson. Also, LEP II has the possibility of increasing its reach in both scenarios by increasing its center-of-mass energy.

There is one set of experimental observables which we have not discussed here, namely the one-loop corrections to the LEP observables and their dependence on the supersymmetric parameters. In the context of $SU(5) \times U(1)$ supergravity these observables have been discussed in Ref. [39, 20], where it was concluded that as long as $m_t^{\text{pole}} \lesssim 170 \text{ GeV}$ there are no constraints on the model parameters at the 90% C.L. One of these observables, namely the ratio $R_b = \Gamma(Z \rightarrow b\bar{b})/\Gamma(Z \rightarrow \text{hadrons})$ has been measured more precisely during the past year [40] and its value still remains more than 2σ above the Standard Model prediction, for not too small values of the top-quark mass. Recently in Ref. [41] it has been argued that supersymmetry could provide a better fit to this observable should the chargino and the lightest top-squark be both light. These conditions could be satisfied in the dilaton scenario discussed above, although an explicit calculation of this observable is required to be certain.

As a final experimental consequence of these models, we have calculated the supersymmetric contribution to the anomalous magnetic moment of the muon (as described in Ref. [42]), which is shown in Fig. 16. The arrow points into the presently experimentally allowed region. The upcoming Brookhaven E821 experiment (1996) [43] aims at an experimental accuracy of 0.4×10^{-9} , which is much smaller than the moduli scenario prediction. This indirect experimental test is likely to be much more stringent than any of the direct tests discussed above. To close, we re-iterate that these one-parameter no-scale supergravity models would become “no-parameter” models once the no-scale mechanism is implemented in specific string models, thereby determining the value of the ultimate parameter.

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Figure 1: The one-dimensional parameter space of strict no-scale $SU(5) \times U(1)$ supergravity – moduli and dilaton scenarios. In the moduli scenario results are rather m_t dependent ($m_t^{\text{pole}} = 160, 170, 180 \text{ GeV}$ are shown). In the dilaton scenario $m_t^{\text{pole}} = 160 \text{ GeV}$ is taken and $m_t^{\text{pole}} < 165 \text{ GeV}$ is required. Points excluded by $B(b \rightarrow s\gamma)$ are denoted by crosses (\times), those consistent with the Standard Model prediction are denoted by diamonds (\diamond), and the rest are denoted by dots (\cdot).

Figure 2: The chargino and neutralino masses (in GeV) versus the lightest chargino mass in strict no-scale $SU(5) \times U(1)$ supergravity – moduli and dilaton scenarios. The following relations hold: $m_{\chi_2^0} \approx m_{\chi_1^\pm} \approx 2m_{\chi_1^0}$, $m_{\chi_{3,4}^0} \approx m_{\chi_2^\pm} \approx |\mu|$.

Figure 3: The slepton ($\tilde{e}_{L,R}, \tilde{\tau}_{1,2}, \tilde{\nu}$) and Higgs-boson masses (h, A, H, H^+) as a function of the chargino mass in strict no-scale $SU(5) \times U(1)$ supergravity – moduli and dilaton scenarios. Also shown is the calculated value of the Higgs mixing parameter μ .

Figure 4: The first- and second-generation average squark mass (\tilde{q}), the gluino mass (\tilde{g} , dashed lines), the sbottom masses ($\tilde{b}_{1,2}$, $m_{\tilde{b}_2} \approx m_{\tilde{q}}$), and the stop masses ($\tilde{t}_{1,2}$) as a function of the chargino mass in strict no-scale $SU(5) \times U(1)$ supergravity – moduli and dilaton scenarios. Note $m_{\tilde{q}} \approx m_{\tilde{g}}$ and that \tilde{t}_1 can be quite light in the dilaton scenario ($m_{\tilde{t}_1} > 67 \text{ GeV}$).

Figure 5: The calculated value of the relic density of the lightest neutralino ($\Omega_\chi h_0^2$) as a function of the chargino mass in strict no-scale $SU(5) \times U(1)$ supergravity – moduli and dilaton scenarios for $m_t^{\text{pole}} = 160$ GeV. The dotted line in the moduli scenario corresponds to $m_t^{\text{pole}} = 180$ GeV. Note that $\Omega_\chi h_0^2$ is sizeable but within cosmological limits.

Figure 6: The branching fraction $B(b \rightarrow s\gamma)$ as a function of the chargino mass in strict no-scale $SU(5) \times U(1)$ supergravity – moduli and dilaton scenarios for $m^{\text{pole}} = 160 \text{ GeV}$. The dotted lines above and below the solid line indicate the estimated theoretical error in the prediction. The dashed lines delimit the Standard Model prediction. The arrows point into the currently experimentally allowed region. The dot-dash line in the moduli scenario corresponds to $m_t^{\text{pole}} = 180 \text{ GeV}$ (central value).

Figure 7: The chargino and neutralino leptonic and hadronic branching fractions as a function of the chargino mass in strict no-scale $SU(5) \times U(1)$ supergravity – moduli and dilaton scenarios. The sudden drops in the neutralino branching fractions correspond to the opening of the “spoiler” mode $\chi_2^0 \rightarrow \chi_1^0 h$.

Figure 8: The rate for trilepton production at the Tevatron as a function of the chargino mass in strict no-scale $SU(5) \times U(1)$ supergravity – moduli and dilaton scenarios. The present CDF upper bound is indicated by the dashed line, and the estimated reach at the end of Run IB is bounded by the dotted lines.

Figure 9: Top-quark branching fractions for $m_t^{\text{pole}} = 160 \text{ GeV}$ in strict no-scale $SU(5) \times U(1)$ supergravity – dilaton scenario.

Figure 10: The lightest Higgs-boson mass as a function of the chargino mass in strict no-scale $SU(5) \times U(1)$ supergravity – moduli and dilaton scenarios. Note that the predicted mass ranges do not overlap and that a lower bound on m_h translates into a lower bound on the chargino mass. Also shown are the Higgs-boson branching fractions into $b\bar{b}$ and $\chi_1^0\chi_1^0$.

Figure 11: The effective cross section $\sigma(e^+e^- \rightarrow Zh) \times f$ [$f = B(h \rightarrow b\bar{b})/B(H \rightarrow b\bar{b})_{\text{SM}}$] for Higgs boson production at LEP II (for the indicated center-of-mass energies) as a function of the Higgs-boson mass in strict no-scale $SU(5) \times U(1)$ supergravity – moduli and dilaton scenarios. The dashed line indicates the estimated experimental sensitivity. Note that the two scenario predictions do not overlap. The deviations of the curves from monotonically decreasing functions of m_h (which coincide with the Standard Model prediction) are due to the $h \rightarrow \chi_1^0 \chi_1^0$ erosion of the preferred $h \rightarrow b\bar{b}$ mode, and could be used to differentiate between the Standard Model Higgs boson and the supersymmetric Higgs boson considered here.

Figure 12: The chargino pair-production cross section into the “mixed” mode ($1\ell + 2j$) at LEP II as a function of the chargino mass in strict no-scale $SU(5) \times U(1)$ supergravity – moduli and dilaton scenarios. The dashed line indicates the estimated experimental sensitivity. Note that the two scenario predictions do not overlap.

Figure 13: The selectron ($\tilde{e}_R\tilde{e}_R + \tilde{e}_R\tilde{e}_L$) and smuon ($\tilde{\mu}_R\tilde{\mu}_R$) pair-production cross sections at LEP II as functions of the slepton mass in strict no-scale $SU(5) \times U(1)$ supergravity – moduli scenario. The dashed lines delimit the estimated experimental sensitivity. In the $\tilde{e}\tilde{e}$ case, for $m_{\tilde{e}_R} > 80 \text{ GeV}$ the $\tilde{e}_R\tilde{e}_L$ channel is closed and thus the kink on the curve.

Figure 14: The lightest top-squark pair-production cross section at LEP II as a function of the top-squark mass in strict no-scale $SU(5) \times U(1)$ supergravity – dilaton scenario. The higher (lower) dashed line indicates the limit of three $2b+2\ell$, $2b+1\ell+2j$, or $2b+4j$ events in $\mathcal{L} = 100$ (500) pb^{-1} of data.

Figure 15: The total elastic supersymmetric cross section (including selectron-neutralino and sneutrino-chargino production) at HERA as a function of the chargino mass in strict no-scale $SU(5) \times U(1)$ supergravity – moduli and dilaton scenarios. The dashed line indicates the sensitivity limit to observe five events in 200 pb^{-1} of data.

Figure 16: The supersymmetric contribution to the anomalous magnetic moment of the muon (a_μ^{susy}) as a function of the chargino mass in strict no-scale $SU(5) \times U(1)$ supergravity – moduli and dilaton scenarios. The arrow points into the currently experimentally allowed region. In the moduli scenario, results are rather m_t dependent ($m_t^{\text{pole}} = 160, 180 \text{ GeV}$ are shown). In the dilaton scenario $m_t^{\text{pole}} = 160 \text{ GeV}$ is taken and $m_t^{\text{pole}} < 165 \text{ GeV}$ is required.